STRAIN SENSOR USING FIBER BRAGG GRATING INTERROGATION

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DEDICATION

I would like to dedicate this thesis to

“ALMIGHTY”

(Who gave me strength, knowledge, patience, and wisdom)

To my beloved “Parents” and “Wife”

(Their support and love, devotion, cares, sacrifices, and prayers)

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In The name of Allah, the Most Beneficent, the Most Merciful

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ABSTRACT

This research aims to focus on analyzing a novel design of strain sensor using Fiber Bragg Grating (FBG) interrogation. Studies on fiber optic sensors reported have mainly focused on FBG wavelength-based monitoring method by using optical spectrum analyzers (OSA). Although FBG has better strain sensitivity measurement, however there have some restriction to monitor by using OSA. The usage of OSA are very costly, bulky and has slow scanning speed. Therefore, research is conducted to design and construct a fully portable, low-cost and low-powered interrogator which is specifically designed to read FBGs within the C-band. An optical strain sensor utilizing reflected light of FBG as input to sagnac loop filter (SLF) is experimentally demonstrated in this work. The proposed SLF has been employed for intensity interrogation of FBG strain sensor where the polarization maintaining fiber (PMF) serves as an edge filter. By monitoring the optical power changes, it is feasible to obtain information that permits strain measurement with a simple and low-cost structure. This work resulted in four milestones. The first is the successful characteristic of strain sensor using FBG 1550nm wavelength. Then, the SLF is characterized using ASE. The output spectrum of SLF is a comb filter and has free spectrum range of 15nm. After that, laser scanning of SLF using TLS is demonstrated. It shows that the optical power is greater than 900μW while the value of R-squared is 0.9931. Finally, by using OSA, the wavelength peak shifts from 1550.088nm to 1550.252nm when the strain changes from 0 to 1000$\mu\varepsilon$, corresponding to a strain sensitivity of 0.0002nm/$\mu\varepsilon$ and R^2 of 0.972 is achieved. Meanwhile, by using OPM, the power increase from 7.01μW to 7.31μW when the strain changes from 0 to 1000$\mu\varepsilon$, corresponding to a strain sensitivity of 0.0003μW/$\mu\varepsilon$ and R^2 of 0.9607 is achieved.

ABSTRAK

Kajian ini bertujuan untuk menganalisis rekaan terbaru berkenaan pengukuran sensor ketegangan berdasarkan teknik interogasi Fiber Bragg Grating (FBG). Kajian terhadap sensor difokuskan kepada kaedah pemantauan gelombang FBG dengan menggunakan penganalisis spektrum optik (OSA). Walaupun FBG mempunyai pengukuran sensor ketegangan yang baik, namun terdapat beberapa sekatan untuk memantau dengan menggunakan OSA. Penggunaan OSA adalah sangat mahal, besar dan pengimbasan yang lambat. Oleh itu, penyelidikan dijalankan untuk merekabentuk teknik interogasi yang mudahalih, kos dan kuasa yang rendah untuk membaca FBG dalam C-band. Eksperimen ini menunjukkan sensor ketegangan optik yang menggunakan pantulan cahaya dari FBG sebagai input kepada *sagnac loop filter* (SLF). SLF yang dicadangkan ini digunakan untuk menginterogasi keamatan ketegangan sensor FBG di mana *polarization maintaining fiber (*PMF) berfungsi sebagai penapisan lebihan. Dengan memantau perubahan kuasa, maklumat berkenaan ketegangan akan diperolehi dengan rekaan yang mudah dan kos yang rendah. Kajian ini menghasilkan empat dapatan utama. Yang pertama adalah ciri-ciri sensor ketegangan dengan menggunakan gelombang FBG 1550nm dibuktikan. Kemudian, SLF dengan menggunakan input ASE dikaji. Spektrum keluaran SLF adalah *comb filter* dan mempunyai rangkaian spektrum sebanyak 15nm. Selepas itu, SLF dengan menggunakan pengimbasan laser input TLS ditunjukkan. Ia menunjukkan bahawa kuasa lebih besar daripada 900μW manakala nilai R^2 ialah 0.9931. Akhir sekali, dengan menggunakan OSA, apabila ketegangan berubah dari 0 hingga 1000με, puncak panjang gelombang berubah dari 1550.088nm kepada 1550.252nm, bersamaan dengan kepekaan ketegangan ialah 0.0002nm/με dan R^2 ialah 0.972 telah dicapai. Sementara itu, dengan menggunakan OPM, terdapat peningkatan kuasa dari 7.01μW hingga 7.31μW iaitu bersamaan dengan kepekaan ketegangan ialah 0.0003μW/με dan R^2 ialah 0.9607 telah dicapai.

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LIST OF SYMBOLS AND ABBREVIATIONS

ε	-	Strain variations
$\mu\varepsilon$	-	Microstrain
S	-	Strain sensitivity
λ_B	-	Bragg wavelength
m	-	meter
cm	-	centimeter
mm	-	millimeter
µm	-	micrometer
nm	-	nanometer
km	-	Kilometer
Λ	-	Grating pitch
°C	-	Degree Celsius
L	-	Length
ΔL	-	Elongation of length
ŋeff	-	Effective refractive index of optical fiber
Hz	-	Hertz
dB	-	decibel
ms	-	milliseconds
µW	-	microwatt
VDC	-	DC Voltage
mA	-	milliampere

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CHAPTER 1

INTRODUCTION

The overview of the improvement strain sensor using Fiber Bragg Gratings (FBG) interrogation measurement is described in this chapter. This introduction consists of the history of analyses, difficulty report, aims of the analysis's, coverage of a project, significant of studies and thesis outline.

1.1 Background of Studies

Year by year, optical sensor era has been gaining improved interest, mainly within the area of infrastructure monitoring technology. It's an equipment that makes use of fiber-optic technology for sensing and measuring physical portions, including strain, pressure, temperature, vibration and displacement. These sensors can handle intense situations due to resistant to electromagnetic interference, excessive sensitivity, light weight and long lifetime. Conventional strain devices were long-standing used to tracking structural modifications, however, now this instrument lack of durability and accuracy. Nowadays, transport medium is given new useful. However, other optical components, including reflectors and wavelength selectors additionally must be advanced to the rapid technology improvement, user-friendly and reasonable-price device [1].

Optical strain sensor, based on FBG has been a well-known sensing tool through the way of tracking wavelength shift of the grating to the strain variation. FBG sensors are gaining increasing attention inside the subject of infrastructure monitoring technology. It operates on very different standards than an electrical strain sensor. A periodic switch of the refractive index in a fiber optics is main characteristics of FBG. A wavelength particular selector can be used as a result of this grating. The selective property has made FBGs and vital device in telecommunication, especially in sensor and different applications using optics. Its capability in measuring the pressure, displacement, strain and temperature had proven. FBGs packages may be discovered within the medical discipline as nicely within the structural health monitoring (SHM). The benefits of sensors in fiber-optic are immunity to electromagnetic interference, small size, actual-time size, fast response, disbursed sensing, elimination of the common calibration, excessive multiplexing skills and as well as localized sensing vicinity [2]. These sensors are thoroughly proper to the new substances of glass and carbon fiber bolstered composites, which are frequently used for notably pressured buildings, in airplanes and wind power plants.

In fundamental, FBG is a microstructure created with the aid of enhancing a preferred single mode fiber and germanium doped alongside ultra violet (UV) laser. It generates a periodic variation inside the refractive index of a fiber optics. When light travels alongside the fiber, all wavelengths are transmitted through the grating while the bragg grating will be reflects-back a completely narrow variety of wavelengths. The wavelength at which this reflection happens is known as the Bragg wavelength. The length of FBG increases or decreases due to the physical straining or compaction of the fiber optic. These transformation outcomes in a change inside the Bragg wavelength, then the interrogator will detect and recorded.

An interrogator, also referred to as measurement unit or data-acquisition device, is an optoelectronic instrument, which permits the analyzing of optical FBG sensors in static and dynamic monitoring programs [3]. An interrogator can measure a massive sensing network composed via various forms of sensors consisting of strain, temperature, displacement, acceleration and tilt, connected alongside more than one fiber, by using acquiring data concurrently and at different sampling rates. during data acquisition, the interrogator measures the wavelength related to the light reflected through the optical sensors and then converts it into engineering units [4]. There are numerous techniques, used as fiber-optic sensors, which includes: Microbend, FBG, Fabry-Perot, Michelson and sagnac loop for interferometer and sensor [5][6].

This study discovered a problem to be approached which an FBG strain sensor interrogator that desires for use optical power meter (OPM) that replaces the bulky and expensive optical spectrum analyzer (OSA) device. Additionally, it needs to be portable and much reduce in price in comparison to the system that was used previously. For this task, the FBG and sagnac loop filter (SLF) are used. This FBG

1550nm is cascaded with SLF using PMF. Broad beneficial spectral bandwidth, polarization independence to input light and excessive resistance to any adjustments and low insertion loss was revealed from a PMF sagnac loop filter. Those specific characteristics create it a favorable wavelength-selective comb filter for multi-wavelength technology in the fiber optics [7]. Though, PMF sagnac filters are suffering by surrounding modifications, for example, temperature, that ends up in a slow drift of the peak transmission wavelengths [8]. Sagnac loop filter is most, famous technique due to; it is straightforward, excessive sensitivity, smooth to manufacture and appropriate, for many unique fibers. For these benefits, it, is used in this research. SLF consists of coupler, fiber optic, and source of light [9].

1.2 Problem Statement

Fiber-Optic Sensors were advanced in specific sensing programs because of their massive benefits, as an example, precision concentration low price, and resistance to electromagnetic waves. In recent times, many strain sensing devices use optical fiber applications.

Strain is a measure of the deformation, which represents the displacement between particles in the matter with respect to a reference length. In designing these optical strain sensors, the strain instrument is implemented. FBG has better strain sensitivity measurement [10]. The interest and prerequisite for high-sensitivity sensor in one-of-a-kind of applications are high. Be that as it may, conventional strain sensors cannot supply pleasurable high sensitivity measurements,

Research on fiber-optic sensors mentioned to this point had, in particular, targeted on wavelength-based tracking technique with the aid of using OSAs. However, it's far very expensive, bulky and has been slow scanning speed, therefore, increases the complexity of the sensor structures and boundaries their realistic packages [10]. This is the challenge that world dealing with these days. FBG Interrogation technique using a power ratio from power meter measurement can overcome this challenge.

1.3 Objectives of the Studies

The main objectives of this project are to develop and demonstrate experimentally strain measurement sensor using FBG interrogation.

The main objectives of this project are:

(i) To study and analyse wavelength shift in FBG strain sensor.

(ii) To investigate strain sensitivity and improve the performance of FBG for strain sensor with SLF.

(iii) To analysis the result measured by OPM and OSA.

1.4 Scope of Project

Fundamental of stress sensor FBG interrogation are studied and mentioned. The strain on bragg grating will be applied by increasing the length of the fiber. Develop the filter optical strain sensor by using SLF. Records from sensors will be obtained in the OSA and LabVIEW software to get the wavelength dips/peaks of the strain and compare with the OPM. Repeat test with different strain will be carried out to obtain graph analyzing, which then can be compared for further analysis.

1.5 Significant of Studies

This research can be a reference to the improvement of measuring strain sensors. The use of OPM rather than OSA makes those studies in value-effective interrogation of fiber sensors based on an FBG. As a result, this study has the benefit in the further improvement of strain measurement.

1.6 Thesis Outline

This project report is split into 5 chapters.

Chapter 1 discloses the overview of the report, where it tells about the studies perspective, contribution of the project, the motivation to problem statement, the significant of studies, objectives of the studies and the scope of the studies. It is also consisting of the outlines of this thesis.

Chapter 2 covers the literature review of the details of fiber-optic sensors, particularly on FBGs, fabrication techniques and interrogation systems. It explains extra thoroughly about the overall methods of strain sensor, filter and related recent literature will be elaborated. The review consists of various present optical sensors and its principle. Finally, it includes descriptions for the apparatus that are used.

Chapter 3 emphases on the research methodology of the stress sensor, initially from the measurement setup for the strain measurement of the sensor until get the result. After that, research technique, research improvement and description of related devices that are used in the set up for the interrogator of strain sensor with the SLF will be explained.

Chapter 4 consists of on measurement finding. It will discuss the results that relate to the goals of research with a purpose to enhance the overall performance of FBG for strain sensor. Each subtopic covers the explanation of experimental setup and result that obtained. The spectrum characteristics of the interrogator could be used as an evaluation with the interrogation that performed.

The final chapter, chapter 5 concluded all the research work, and all the results will be analyzed. Based on the evaluation, conclusions are then drawn from the result based totally on OSA and OPM. Recommendation of future work for improvement over the present designs is mentioned at the end of the chapter.

1.7 Chapter Summary

On this chapter, opening for the work has been demonstrated. It consists of the background of the strain sensors and the motive for keep the studies in this area, difficulty report, aims of studies, coverage of work, significant of studies and thesis outline.

CHAPTER 2

LITERATURE REVIEW

This chapter describes the overview on fiber-optic sensors and fundamental. This studies assessment also includes the FBG setup as a sensor. That is accompanied via covering a method on FBG interrogator as carried out in preceding investigations, and lastly determining on the approach of preference.

2.1 Introduction

Sensors are now grown to be essential in order to improve productivity. There is a wide variety of sensors, each has its strengths and weaknesses. Some examples of sensor inside the marketplace are photoelectric, vision, laser, inductive displacement, proximity, ultrasonic, contact-type displacement, and fiber-optic sensors.

Electromagnetic waves in the visible bands of an electromagnetic spectrum can transport by fiber optic, which is a quite flexible and obvious dielectric material medium [11]. The optical fiber comprises of three specific layers, which are coating, cladding and core. Core is the inner section of the fiber-optic and is surrounded in the cladding. Those layers are protected with the aid of fiber's coating. The fiber optic core refractive index can be uniform or graded, and the cladding index is commonly constant. Overall inner reflections between the core and the cladding are based totally from Light guiding and propagation in an optical fiber [12]. For light guiding, core's index needed to be larger than an index of cladding. Light power propagates inside the center layer and only a minor fraction of the light power moves inside the cladding. The cladding thickness is commonly greater in order that the coating has no impact during the light propagation within the fiber-optic construction. The fundamental construction of a fiber optic is shown in Figure 2.1 which has an exterior covering to protect and harden the fiber, a cladding and a central core.

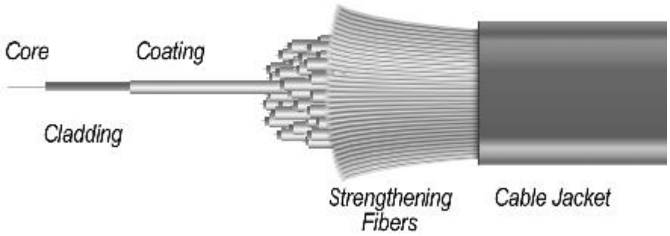

Figure 2.1: Essential construction of a fiber optic

Fiber-optic sensors have great ability in lots of applications while maintaining superiority over non the fiber sensor in a few fields of sensing technologies. It's been one of the most essential devices in severe industrial packages, as an example, in civil engineering, oil and gas and aerospace, because of their specific benefits of lengthy lifetime, light weight, immunity to electro-magnetic interference and excessive sensitivity [2].

FBG interrogation means to convert wavelength shift into a variation of electrical signal with adequate characteristic to obtain the information about the measurand [13]. FBG has been a famous sensing element by tracking wavelength shift of the grating to the strain variant. The sensing principle of FBG sensors includes detecting the central wavelength variation. There have a lot of interrogation techniques of FBGs have been proposed for the year, and it will describe in this section.

An SLF definitely consists of a coupler. It is located in the two ends of which are spliced to the two ends of a segment of fiber optic. The function of sagnac loop is as a reflector or periodic filter relying on the birefringence with the fiber loop. For example, when there is no birefringence within the fiber loop, sagnac loop is as a reflector.

The last subsection of this section discusses briefly the relevant device and high-quality practices whilst implementing a strain sensor the usage of FBG interrogation set up in the laboratory. It is including the, amplified spontaneous emission (ASE), optical circulator, coupler, OSA and OPM.

2.2 Overview of Optical Fiber Sensor

Laser light was discovered in 1960. After that, investigation of the implementation of a fiber optics for sensing, data communications, and many different applications widen [14]. Eventually, the fiber optic in the communication system has emerged as the greatest desire for gigabit's transmittance of data. This kind of communication is used to transmit data, video, voice, telemetry and computer network. In order to transmit the data over a fiber, the light wave is used by converting electronic signals into light. Light weight, low attenuation, smaller size, long distance signal transmission, large bandwidth and transmission security are some of the awesome features of this technology [15].

Significantly, in recent advances fiber-optic technology has changed the communication field. The number of fibers-optic sensors products can be expected to grow fairly in the years to come as rapid progress continues. The ultimate revolution seemed as inventors invent sensors from the combination of product of optoelectronic devices with fiber-optic devices. The various components related to these devices are frequently developed for the fiber-optic sensor applications. The potential of the fiber-optic sensors has improved inside the area of conventional sensor.

The fiber-optic sensors use fiber optic or sensing component as shown in Figure 2.2. Those sensors are used to experience a few quantities like strain, temperature, vibrations, displacements, rotations or concentration of chemical type. Fibers have such a lot of uses in the field of remote sensing because it requires no electric power on the faraway region and has small size.

Fiber-optic sensors are ideally suited for insensitive situations, together with excessive vibration, heat, noise, moist and risky environments. Those sensors can be without a difficulty place in small regions and can be located effectively anyplace adaptable fibers are desired [16]. Optical frequency-domain reflectometry is a device to calculated wavelength shift while time-delay of the fiber-optic sensors can be determined using a tool such as an optical time-domain reflectometer.

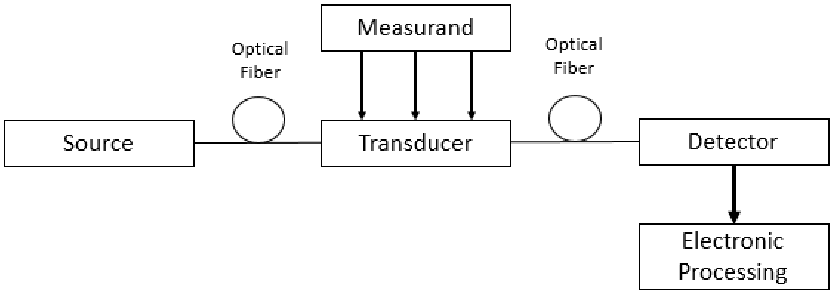

Figure 2.2: Basic elements of an fiber-optic sensor device

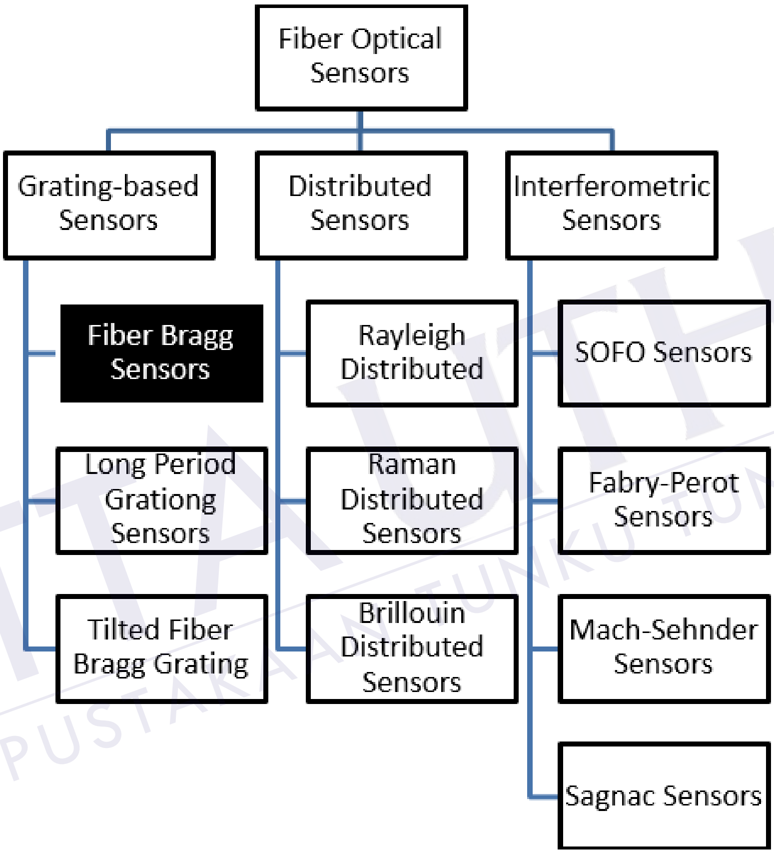

Figure 2.3: Review of fundamental concepts and varieties of fiber-optic sensors

In overall sensor can be classified into 3 classes [17]:

1. Grating-based
2. Distributed
3. Interferometric

Each class has a huge range focused on various kinds of assessments and applications. Information is exhibited in Figure 2.3. An interferometer sensor is produced through an intrinsic or extrinsic interferometer hollow space along an optical path [14]. The changes of the phase difference between 2 interference light waves are reflected through Physical modifications in systems. The character of interference provides the interferometric sensors the ability of calculating very small mechanical deformations improving than microstrain (με). Well-known and applicable interferometer sensors consist of Fabry-Perot and occasional coherent interferometer sensors [15]. There are 3 forms of fiber optic distributed sensors:

1. Optical time-domain reflectometry (OTDR) [18]
2. Raman optical time-domain reflectometry (ROTDR) [19]
3. Brillouin optical time-domain reflectometry (BOTDR) [20]

The highlight (in black) sensor technology in Figure 2.3 represents the kind of fiber that used in this research. The most perfect grating-based sensors and feature so far been extensively used is FBG sensors. Bragg wavelength is a selected wavelength which the incoming light will be reflected and transmit the other wavelength without changing its belongings as shown in Figure 2.4 [17]. Therefore, FBG sensors can be monitored wavelength shift with the aid of the Bragg. Modern technology makes it feasible to multiplex plenty of FBG strain sensors in a single optic fiber and monitors distantly. FBG sensors have the benefits of compact size, low price and good linearity other than wavelength multiplexing functionality.

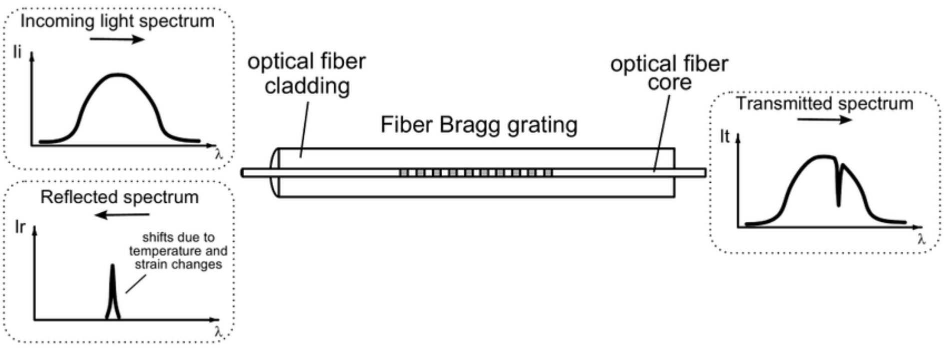

Figure 2.4: Functional principle of an FBG

2.3 Fiber Bragg Gratings (FBG)

The technique of monitoring the optical signal this is reflected by FBG is normally called demodulation. In Figure 2.5, the FBG demodulation setup works as follows: a broadband fiber-coupled source of light injects a light signal into an optical fiber. This light source can be, for instance, an ASE light source. The broadband light signal (solid arrows in Figure 2.5) reaches an optical circulator through port 1. Optical circulators are passive devices, which are employed in optical networks to direct the transmitted signal in a single direction; this is, the signal entrance port 1 is aimed to port 2, while the signal coming from port 2 is pointed to port 3. Consequently, the broadband light signal reaches the FBG that is connected to the optical circulator via port 2, and grating will make a narrowband spectral component on the Bragg wavelength reflected.

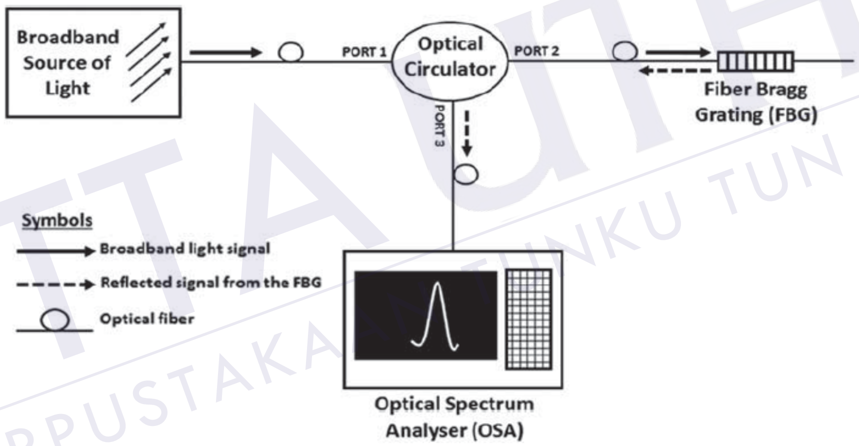

Figure 2.5: Basic demodulation setup to recover the reflected signal from the FBG

The narrowband reflected signal (dotted arrows in Figure 2.5) from the FBG comes from port 2 directly to port 3, reaching the OSA, which displays the reflected spectra on the screen. OSAs do not normally function at high sampling rates, so, for some applications, other demodulation schemes can be considered. However, this instrument suits most laboratory applications. The demodulation setup depicted in Figure 2.5 can be used to monitor the reflected spectra as the grating is being inscribed, that is, the setup is employed to verify if the grating is being formed as the reflected signal begins to appear on the OSA display and usually grows in terms of optical intensity. The operating principle of fiber-optic sensor using FBG is shown in Figure 2.6.

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